MEETING THE CHALLENGE OF MANNED LUNAR AND MARTIAN EXPLORATION

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As the U.S. space program plans for a return to the Lunar surface and ultimately for a mission to Mars, space suits and portable life support systems will have to keep pace to meet the exploration mission requirements. The systems currently in use with the Shuttle program will not be adequate for exploration on the Martian surface or for extensive exploration and work on the Lunar surface. Currently, there are too many unknowns regarding locomotion and work physiology in reduced gravity to accurately design advanced suits and life support systems for routine extravehicular activity (EVA). It would be unwise and costly to arbitrarily develop new designs without first studying how the human body moves and works in these environments. This paper discusses the current state of the art of EVA space suit and portable life support system (PLSS) design, and how this compares to the requirements for suit and PLSS design to meet the needs of advanced exploration missions. Current research underway in the Extravehicular Systems Branch at Ames Research Center aimed at advanced system design will be highlighted.

THE CURRENT HARDWARE

Although it is satisfactory for the current Shuttle program, the space suit presently used on the Space Shuttle will not be adequate for future advanced missions. The Shuttle suit operates at 4.3 pounds per square inch (psi) internal pressure, requiring an extended decompression profile to allow the EVA astronauts to go from a 14.7 psi craft to a 4.3 psi EVA suit. The Shuttle pressure is first lowered to 10.2 psi for 24 hours before the planned EVA. The EVA crew then breathes pure oxygen for 45 minutes prior to embarking on the EVA. Even after this extensive preparation a significant bends risk on the order of 5% still exists. In addition, the lowered cabin pressure can cause overheating of the air-cooled electronic systems on the shuttle.

The Shuttle suit also requires a great deal of effort to flex the joints because the suit does not maintain a constant volume. When a joint is flexed and then held in a fixed position, the astronaut must contract his/her muscles isometrically to keep the joint flexed. This extra effort can lead to local muscle fatigue early in an EVA.

The extravehicular mobility unit (EMU) is not designed to be space-based since it is not easily maintained nor is it as rugged as would be required for frequent use. It is certified for only 3 uses and then it must be torn down completely and overhauled. These maintenance requirements virtually exclude both the Shuttle suit and EMU from being used for advanced missions.

There are currently two prototype suits developed for 0-gravity (g) EVA use on the Space Station as well as other microgravity situations. Ames Research Center developed the AX-5 and Johnson

Space Center developed the MK III. Both suits operate at 8.3 psi. If used in a 1 atmosphere (atm) base or cabin, these suits minimize prebreath time. These suits were designed for 0-g operations, however, rather than for walking or other planetary surface operations.

REQUIREMENTS FOR ADVANCED HARDWARE

Although there are elements which we know little about, there are some general parameters of advanced suit and PLSS design that can be used in developing advanced concepts. Ideally, advanced design concepts should improve the work capability of the EVA astronaut thereby increasing the amount of productive labor per EVA hour. An advanced suit should also maximize productivity while minimizing fatigue. One way to accomplish this is to minimize both the dynamic and static suit joint flexure forces. The suit mobility joints must also be designed to allow the degrees of freedom and range of motion required to perform the EVA tasks. Emphasis on comfort will be much more important for advanced missions because extravehicular operations have the potential of being much more routine and of longer duration. Designs which were tolerable for short missions with infrequent EVAs won't be acceptable for longer ones.

An advanced suit should also have the correct ratio of suit pressure to base or cabin pressure in order to eliminate pre-breathe and to decrease the bends risk. An advanced concept suit designed to operate at, or very near, cabin or base pressure could eliminate pre-breathe problems. A suit that can operate well at 9 or 10 psi would be ideal if the cabin or base pressure is 14.7 psi.

The remoteness and duration of a Mars mission will require every element of the mission be optimized for function, reliability and efficiency. Logistical problems such as how much support system mass must be launched to maintain the suit/PLSS must be addressed. The weight and volume of the unit could be minimized by efficient packaging. In addition, an advanced suit/PLSS unit must also be easily maintained. If Lunar exploration is to become more routine than what was done in the Apollo program, a new life support system will have to support more physically taxing work and be more efficient at removing metabolic heat quickly and effectively. Research into metabolic rates achieved with varying levels of EVA work may help us to understand what types of heat removal rates a future PLSS would have to provide.

The biomechanical and physiological assumptions about how an advanced concept suit and PLSS must perform need to be confirmed by experiment. Research must be performed and the results compared with mission requirements for extravehicular operations.

CURRENT EXPERIMENTS UNDERWAY AT AMES RESEARCH CENTER

One question that needs to be addressed with regard to an advanced concept PLSS is how to effectively and efficiently maintain thermal comfort throughout an extended orbital EVA. Currently, when more warmth or cooling is needed within the suit, the astronaut controls the action of the liquid cooling garment (LCG) by manually adjusting a knob on the suit. This takes away from an astronaut's work time and it is also inefficient. Operational experience with the current EVA system shows the astronaut's heat balance is poorly controlled, resulting in some areas of their body being

warm while they are simultaneously cold in other areas. Studies show that both skin temperature and internal body temperature may be important indicators of the state of thermal comfort (refs. 1 and 4). Another study purports that a linear relationship exists between skin temperature and metabolic rate and that a linear relationship also exists between the evaporation of sweat and metabolic rate (ref. 3). Therefore it's possible that an advanced heat balance system could "read" an astronaut's metabolic rate by way of some non-invasive sensor and then automatically change its cooling function without the astronaut having to do anything but continue his/her work. This could lead to not only greater overall thermal comfort and a more stable heat balance but it would also allow longer EVA sessions with less chance of astronaut fatigue due to over or under cooling.

In order to pursue this thermal comfort question as well as attempt to simulate the metabolic cost of orbital EVA, a set of experiments was designed to simulate orbital EVA and to quantify the physiological cost of the activity (ref. 12). Using three male subjects, exercise experiments were performed on a unique upper body arm crank device (figs. 1 and 2). The device provides four degrees of freedom of movement: roll, pitch, yaw, and a linear motion aligned with the spine. The bench on which the subject lies is supported by a gimballed shaft. The subject's body weight is counterbalanced by weights at the opposite end of the shaft. Thus, when the shaft is in the unlocked position (the actual EVA simulation situation), the subject reacts all forces at the feet which are secured in foot restraints that do not move relative to the ground. The device can also be used in the locked position in which the shaft remains immobile and the subject does not have to counterbalance himself using his feet.

The first series of experiments which were recently completed were designed to correlate this new exercise technique and to demonstrate its utility as a 0-g EVA work simulation device. Five
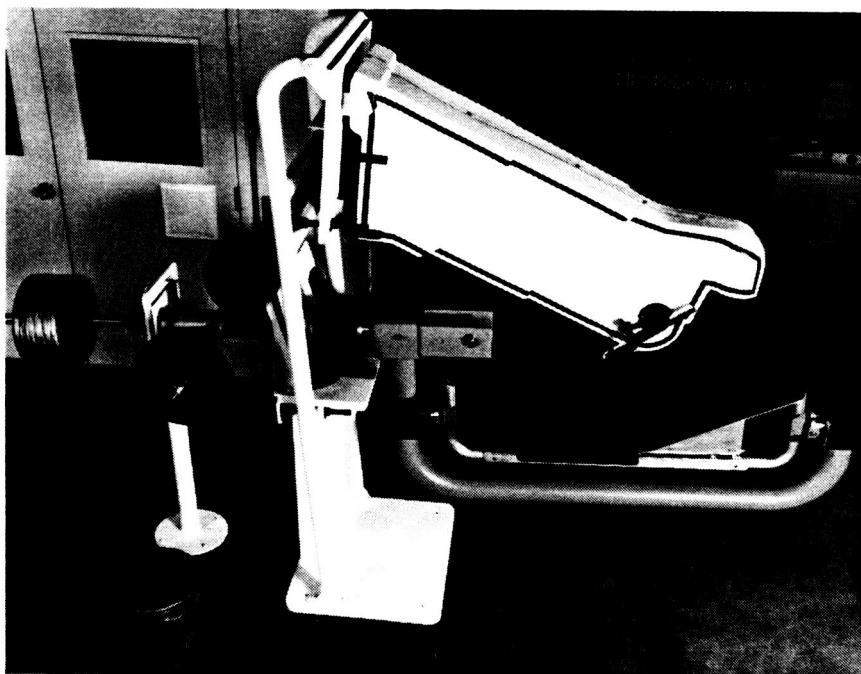

Figure 1. The extravehicular activity simulation device located at Ames Research Center.
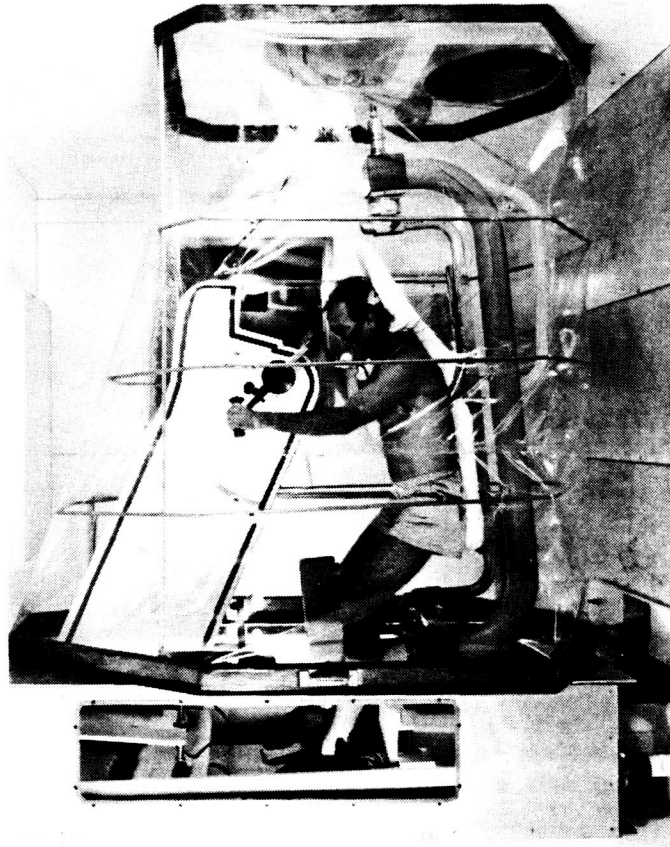
Figure 2. The extravehicular activity simulation device housed in its environmentally controlled chamber.

exercise protocols were used: (1) a low level constant workload (25 watt work output); (2) a moderate level constant workload (65 watt work output); (3) a high level constant workload (100 watt work output); (4) a transient workload; and (5) a maximum output protocol in which the subject cranked as hard as he could for 1 minute after a five minute warm up. For these initial tests, subjects were dressed in exercise shorts with no cooling system. First, a control situation was implemented in which subjects sat upright in front of the ergometer and performed the various protocols to correlate this exercise device with other upright arm crank research. Preliminary findings on oxygen uptake are comparable to other studies utilizing upright arm crank exercise (refs. 2, 7, and 10) (fig. 3). The subjects were then put on the device in the supine position and did all protocols at least three times in both a locked and unlocked position. Subjects came to the lab 2 or 3 times per week and performed 1 protocol per session until all test situations were completed. Subjects performed identical work protocols in both the locked position and unlocked position in order for the investigators to observe the metabolic rate and other physiological parameters when isometric lower body stabilization forces had to be performed by the subject.

Results from these experiments are currently being reduced and analyzed but preliminary findings suggest the average metabolic rate reached in three of the protocols, the low constant workload, the moderate constant workload, and the transient workload, most closely mirror the average
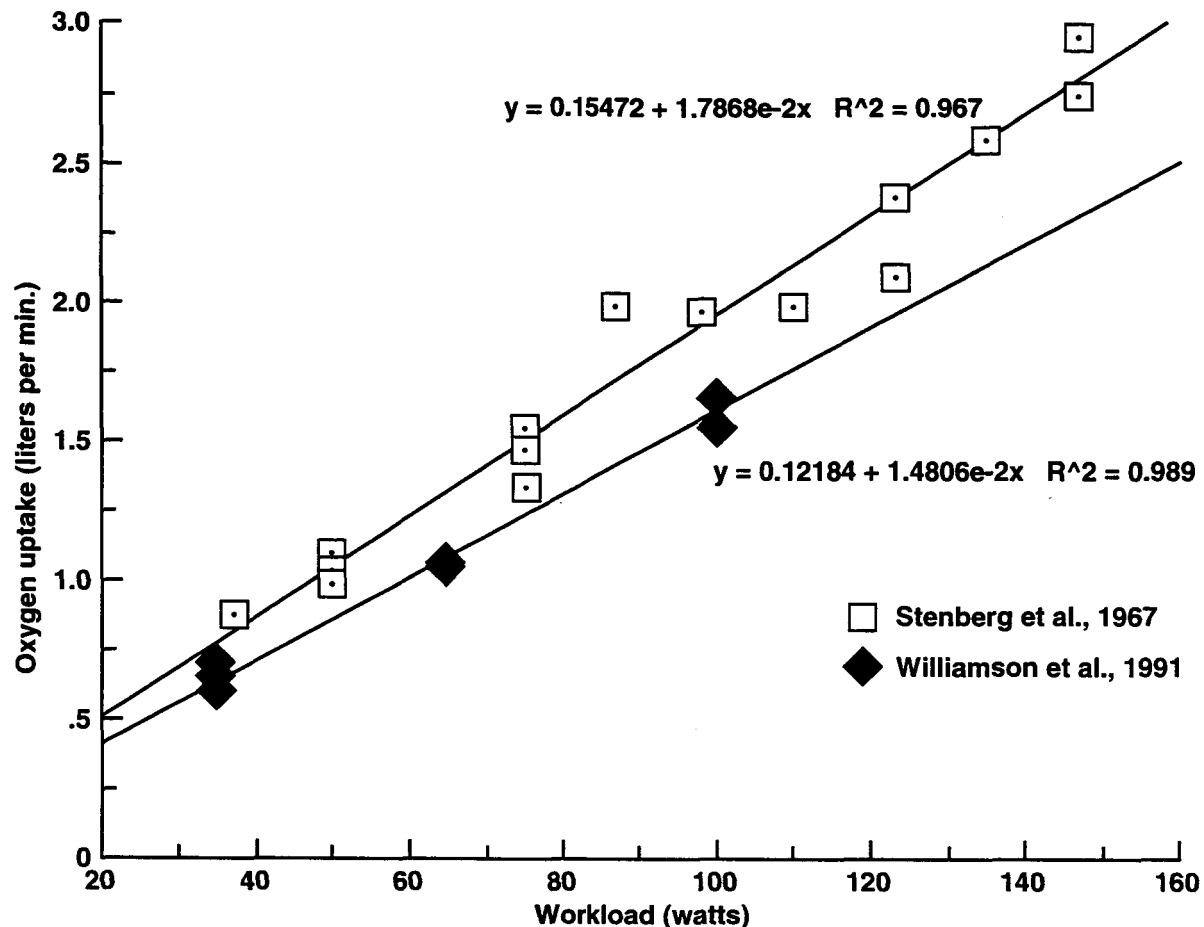
Figure 3. Comparison of oxygen uptake between two seated upright arm crank ergometry studies. In Williamson et al., (ref. 12), 3 male subjects exercised at 35, 65, and 100 watt constant work outputs. In Stenberg et al., (ref. 7), 6 male subjects exercised at various constant workloads from 1-4 sessions each.

metabolic load of actual EVAs (refs. 5, 8, and 9) (table 1). This suggests the exercise protocols may not only replicate the generic muscular movements of an average EVA (i.e., dynamic upper body work combined with isometric lower body work), but that the metabolic loads on the subject may be quite similar to that of EVA astronauts. Although the higher constant workload protocol elicited higher average metabolic costs than those thought to occur during orbital EVA, these data will indicate the upper limits that must be understood in order to build a controller capable of keeping an astronaut comfortable during short periods of hard work.

Once data analysis is finished, experiment findings will be submitted in the form of a formal journal article. In addition, another set of similar exercise experiments with a larger subject pool will be conducted to reconfirm the data. After analyzing data from these follow-on experiments, a prototype controller will be developed. Exercise experiments with subjects wearing the prototype controller will then be conducted to provide more information on how heat balance and thermal comfort during an EVA can be manipulated by a control system.

Table 1. Comparison of metabolic rates on actual mission EVAs (refs. 5, 8, and 9) and a simulated EVA study performed at Ames Research Center (ref. 12).

ACTUAL EVA METABOLIC RATES FROM VARIOUS PROGRAMS*		
Program	Mean rate for entire program (kcal/hour)	Range of rates for entire EVAs (kcal/hour)
Apollo 1/6-g 0-g	235 151	197-302 117-504
Skylab	238	145-330
Shuttle	197	152-275

METABOLIC RATES FROM SIMULATED EVA STUDY (SUPINE UNLOCKED POSITION) AT AMES RESEARCH CENTER**		
Exercise protocol	Mean rate for entire test***(kcal/hour)	Range for entire test***(kcal/hour)
Low (constant 35 watt output)	154	32-401
Moderate (constant 65 watt output)	219	24-654
High (constant 100 watt output)	352	34-849
Transient	225	44-676

*Three methods were used to estimate real-time metabolic rates:
1. Heart rate
2. Oxygen usage (computed from the decrease in oxygen bottle pressure per unit time).
3. Difference in temperatures of the coolant water flowing into and out from the LCG.
**Standard laboratory method of measuring oxygen consumption/carbon dioxide production with gas analyers was used.
***Excluding 2 minute warm up at beginning of tests.

Another factor that must also be understood to optimize an advanced suit and PLSS is an understanding of both the allowable load carrying limits and acceptable perturbations to the center of gravity (c.g.) in simulated planetary surface EVAs. This will provide guidance as to how much a PLSS can weigh and how/where the load of the unit should optimally be placed relative to the astronaut's body. In the Martian environment of 3/8-g, the weight of the unit is especially significant as is the placement of the PLSS upon the suit. A unit that is too heavy or that has the PLSS placed in such a way as to hinder the astronaut's activity would make EVAs difficult and possibly dangerous.

A set of experiments is currently being performed to assess the effect of reduced gravity levels on various measures of work performance in human load-carrying capability during planetary EVA (ref. 11). Tasks such as walking, kneeling down from and returning to an upright posture, lifting boxes of graduated weights, and positioning boxes at various locations while the subject's c.g. has been displaced from normal are activities of interest to the investigator in order to observe how load placement affects astronaut movement and productivity.

The first round of these experiments was conducted on the KC-135 aircraft at NASA Johnson Space Center. During 2 days of testing, 50 Martian and 95 Lunar parabolas were flown. Five male subjects wore a Variable Load Positioning Backpack (VLPB) which placed a 50 pound load at one of two extreme locations: high on the back, at the location of the current shuttle PLSS c.g.; or low on the front torso, at the same horizontal distance from the body's centerline as the high back location but at the vertical height of the normal body c.g. Subjects performed several lifting, positioning, and treadmill walking tasks with the load in the two different locations. All tests were also videotaped for biomechanical motion analysis. After the flights, subjects answered questionnaires regarding comfort, difficulty, stability, and control for each task and load position. Further experiments will be conducted at the Ames Neutral Buoyancy Test Facility (NBTF) where additional measurements of oxygen consumption, carbon dioxide production, heart rate, foot to treadmill contact forces, joint movement ranges, and body segment trajectories will be taken in order to further investigate these issues. Once data have been analyzed, an analytical biomechanical model will be developed to provide a more thorough understanding of the role of reduced gravity in human load carrying and optimal load placement. Results from this study are expected to have significant effect on the design of future planetary EVA suits and PLSS design/placement by giving design engineers new information on optimal load placement and suit structure.

Modeling the biomechanics and mobility of humans performing simple planetary locomotion is a third area that needs investigation in order to drive advanced suit design. Identifying gait, transition speed, and oxygen consumption during locomotion is a critical first step in the understanding of human performance in partial gravity. Quantifying workloads encountered and the energy cost of planetary locomotion will help define oxygen consumption and carbon dioxide production requirements for planetary life support systems.

Newman and colleagues recently completed a study investigating the biomechanics and energetics of locomotion in reduced gravity environments (ref. 6). The study took place at the Ames NBTF. Six subjects (4 male, 2 female) were used in this study. Each subject completed six experimental sessions. One session was a 1-g control experiment with the subject exercising on the treadmill outside the NBTF. The remaining five sessions took place underwater in the NBTF with the subjects breathing through modified commercial diving gear (fig. 4). Partial gravity loads were provided by

an adjustable loading harness on the subjects which distributed lead weights ranging from 0% to 100% of their dry body weight. The subject's body-segment masses and inertial properties determined the amount of weight required to simulate partial gravity loading. Weights were distributed on five regions and balanced across the mass center of the left lower leg, right lower leg, left thigh, right thigh, and torso. Five gravity conditions were simulated: 0-g, 1/6-g, 3/8-g, 2/3-g, and approximately full body loading (90-100%). Subjects walked at three speeds: 0.5 meters per second (m/s), 1.5 m/s, and 2.3 m/s during each of the experimental sessions.

Vertical ground reaction forces were measured during each session while oxygen consumption, carbon dioxide production, and heart rate were sampled. Video data were recorded and manually analyzed by a computer program to encode the limb position. The data revealed a significant ($p < 0.5$) reduction in peak ground reaction force with a decrease in gravity level at all speeds. Stride frequency measurements indicated a general trend toward a loping gait as gravity level decreased. For locomotion at 1.5 m/s and 2.3 m/s, the plot of average stride frequency versus gravity depicted a non-linear reduction in stride frequency as gravity level decreased, while there was no significant difference in foot contact time for various gravity levels. This suggests that the aerial phase (time between toe-off and ground contact of the opposite foot) is significantly longer for partial gravity locomotion because the contact time does not vary with gravity level while the stride frequency
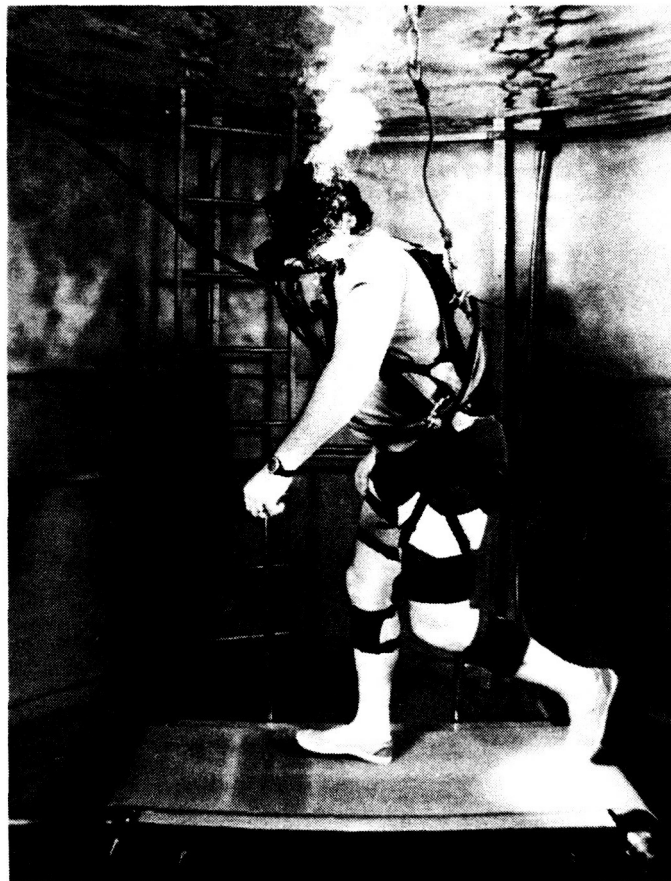

Figure 4. The underwater treadmill at Ames Research Center.

decreases. The extended aerial phase, or reduction in number of strides per minute, is typical of a loping gait in which the subject's ground reaction force is greater than the pull of gravity; the subject essentially propels himself/herself into an aerial trajectory for a few seconds during locomotion.

There was a reduction in oxygen uptake as gravity was decreased from the 1-g level. For locomotion at 1.5 m/s and 2.3 m/s, a continuous decrease in heart rate was seen with decreasing gravity level. However, for locomotion at 0.5 m/s, the results indicated an *increase* in heart rate. This suggests that at low speeds, and low levels of gravity, proportionately more energy is expended in stability and posture control than in locomotion itself. Interestingly, for locomotion at 0.5 m/s during the Martian simulation (3/8-g) subjects commented that this level was the "optimal and most comfortable" of all the partial gravity levels. Newman contends that the g-level threshold for humans being able to locomote in a typical "terrestrial" upright posture using their legs effectively for movement needs to be defined through future experimentation.

These three studies help fill a void in the knowledge on human locomotion and work capability for the entire range of gravity between microgravity (0-g) and 1-g and could, when combined with data from similar future studies, provide substantial information to space suit designers on how the human body moves through space in reduced gravity environments and the energy requirements associated with this movement. By studying how the human body most effectively works in these environments, we will learn not only how to fabricate life support systems that will support such work in space but we will also learn how to keep our astronauts safe. By understanding human physiological limits, we can more adequately plan EVA schedules and planetary activities and extend our exploration capabilities immeasurably.

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BIOGRAPHY

Rebecca C. Williamson, M.S., works with the Extravehicular Systems Branch of the Advanced Life Support Division under subcontract to Sterling Software, Inc. Having expertise in human responses to exercise and human exercise testing, she was hired as a consultant in 1988 to design and develop a human exercise protocol to simulate orbital extravehicular activity and run experiments to assess the physiological cost of the activity. Future research will include additional in-depth study into the metabolic requirements for advanced life support systems. Orbital EVA research has been the main focus of Ms. Williamson's research efforts at Ames, however, she has also participated in AX-5 testing and range-of-motion studies and consults with Branch engineers on biomechanics and human physiology issues relating to advanced life support system development.